INVESTIGATIONS OF VAPOR-CELL CLOCK EQUILIBRATION FOLLOWING INITIAL ACTIVATION: A PROGRESS REPORT

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Abstract

Over the past several years, anecdotal evidence has grown indicating that Rb gas-cell frequency standards exhibit a long "equilibration" period of somewhere between 30 and 70 days following their initial activation. The mechanism driving this behavior is not well understood and has been the subject of debate. Generally, lamp intensity has also been observed to undergo a slow variation following the clock's turn-on, and since the clock's resonant frequency depends on light intensity via the light-shift effect, there has been speculation regarding the light-shift as a possible mechanism for long-term equilibration. However, helium permeation has also been suggested as a contributing mechanism, since the gas cells are manufactured free of He and over time atmospheric He must permeate into the cells changing the clock frequency via the pressure-shift effect. In order to characterize the nature and discern the mechanism of equilibration in Rb clocks, we have initiated a project to study the long-term (i.e., > 100 days) deterministic variations of Rb clocks from different manufacturers. Though our preliminary data confirms the anecdotal findings, the data at present are ambiguous regarding a causal relationship between long-term lamp-intensity change and clock-frequency change.

INTRODUCTION

When a rubidium atomic clock is first activated, the temperature of the lamp, filter-cell, and resonance-cell increase, and as a consequence the alkali vapor density in each of these clock elements increases. Due to the light-shift **[1]** and position-shift effects **[2]**, these variations in alkali density give rise to a clock frequency change that proceeds until the clock's temperature has reached steady-state. As illustrated in Figure 1a, the clock "warms-up" to its true steady-state temperature conditions within roughly a day. Following this warm-up period, the clock frequency continues to change, though now at a much-reduced rate, and this slower frequency variation has often been termed frequency "aging." However, over the past years evidence has accumulated suggesting that the frequency-aging rate is not constant following initial clock activation. Rather, the aging rate slows down over a period of months, until after about 6 months of continuous operation the clock frequency displays what may best be described as the clock's "true" frequency aging: a very linear and very slow frequency change with time. As illustrated in Figure 1b, we distinguish between these two regimes of long-term, deterministic, frequency-change behavior by reserving the term frequency aging for the quiescent linear process that takes place well into the clock's operating life, and by defining a new term, clock-frequency "equilibration," as the temporal change in clock frequency that occurs between clock warm-up and true aging.

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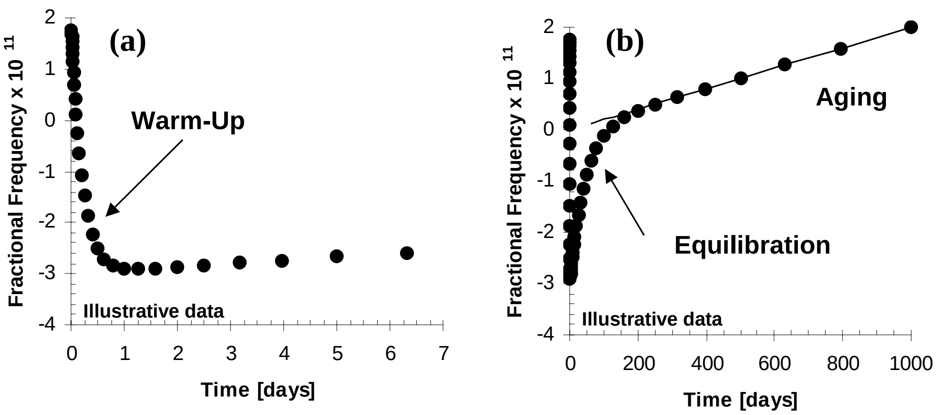

Figure 1. Illustration of the nominal temporal change of a rubidium clock's frequency with time. As shown in (a), within the first day the clock warms up, and thereafter displays a slow frequency variation with time. On a longer timescale, however, as illustrated in (b), the rate of frequency change after warm-up generally slows down, until after several months the clock reaches its quiescent frequency-aging rate. To distinguish these two long-term, deterministic, frequency-changing processes, we reserve the term frequency aging for the clock's behavior well into its life and define the term frequency "equilibration," as illustrated in Figure 1b.

From a timekeeping system's operational standpoint, the issue of gas-cell clock equilibration can be fairly important. For example, in situations where diverse spacecraft clocks are slaved to a master satellite rubidium (Rb) clock, for example in the Milstar and Advanced-EHF systems **[3]**, good constellation timekeeping requires a master satellite whose Rb clock has completed equilibration. Consequently, there is a need to: 1) demonstrate the universality of gas-cell clock equilibration, 2) discover the underlying mechanism(s) driving the equilibration, and 3) develop (if possible) strategies to speed up the equilibration process. With this motivation, we have begun a project to study gas-cell clock equilibration. In the present work, we describe our preliminary results examining the frequency variations of four gas-cell clocks over the period of about a year following their initial activation.

EXPERIMENT

At present we have three Frequency Electronics Inc. (FEI) Rb clocks under test (FEI model 5680A) along with one Stanford Research Systems (SRS) Rb clock (model PRS10). As the study proceeds, other clocks from different manufacturers will be incorporated into the study's database. Figure 2 shows our testbed in schematic form. The oscillators are housed in a temperature-stabilized oven to minimize the effects of room temperature fluctuations on frequency with the oven is set to 48.2^{o}C. Initially, we had set the oven to maintain a temperature of 48.0^{o}C, with the oven cycling through heating and cooling using CO_2 expansion. However, we observed frequency oscillations in two of the clocks that were correlated with the cooling cycle. (Vibrations in the system occurred when the CO_2 expansion valve was opened.) Consequently, we reset the oven temperature to 48.2 degrees so as to effectively eliminate the cooling cycles of the oven. As a result, the frequency oscillations that we had observed in two of the clocks subsided. The output frequency of each Rb oscillator is connected to a separate channel of a Timing Solutions Corporation (TSC) 55700 Precision Time and Frequency System. The crystal voltage, lock indicator, and lamp-intensity voltage of the clocks are monitored with a 16-bit A/D board and recorded by a computer. The air temperature in the oven, the temperature of the clocks (the board that the clocks are mounted on), and the ambient room temperature are also recorded. Since our SRS clock was placed

under test prior to completion of our testbed, the SRS clock was not placed in the oven, but was allowed to continue operation in the laboratory's ambient temperature environment. The SRS clock's output is also connected to a channel of the TSC, and the clock's crystal voltage, lock indicator, and lamp intensity are monitored with a 12-bit A/D board and stored on a separate computer. For completeness, we note that all of the Rb clocks presently under test correspond to a separated filter-cell design **[4]**, though we anticipate placing integrated filter-cell design clocks under test in the future.

The output of a Frequency and Time Systems (FTS) 5030A Cs beam clock is also connected to the TSC measurement unit, and is taken as our house standard. At each second during data acquisition, the TSC measures the phase of each input channel relative to an internal oscillator, and the output is sent to a computer where it is stored for later analysis. The phase data that are output by the TSC are used to compute fractional frequencies of each Rb clock relative to the Cs standard at each second.

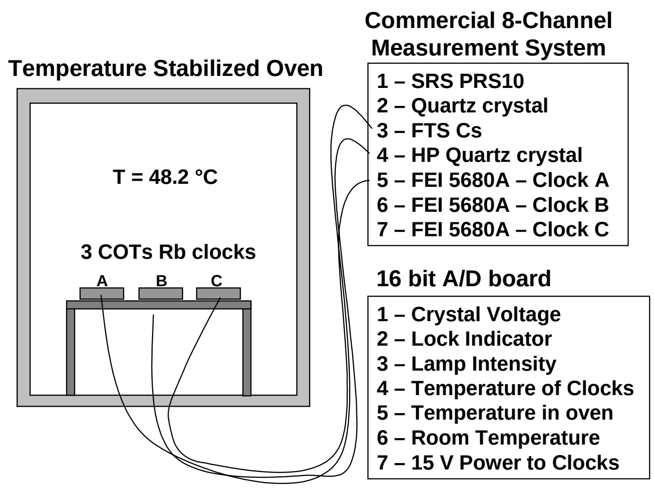

Figure 2. Illustration of the measurement system and clock testbed as described in the text.

PRELIMINARY RESULTS

Figures 3a and 3b show the "classic" temporal behavior of a Rb clock's output frequency following initial activation. (These data were obtained from one of the FEI clocks under test, and we note here that the other FEI clocks showed qualitatively similar behavior.) In the first day after turn-on (Figure 3a), the clock warms up, and there is a corresponding decrease in light intensity that appears to be strongly correlated with the decrease in clock frequency. Typically, this correlated behavior between clock frequency and lamp intensity during turn-on is associated with the clock's light-shift effect, and in the rest of this presentation *our reference to a light-shift coefficient refers explicitly to this warm-up lamp-intensity/frequency correlation*.* Following the clock's warm-up, in the first 5 to 6 weeks of clock

* The light-shift also depends on the spectral profile of the lamp, which could conceivably change as the lamp warms up and then equilibrates. Nevertheless, we *assume* that after roughly an hour the vapor densities in the lamp and filter cell are close enough to their nominal values so that there is little change in the spectral profiles of the resonance lines impinging on the resonance cell. Nevertheless, we note here that this is an assumption that may require validation at a latter date. For a discussion of the spectral lineshape's role in the light-shift phenomenon,

operation, the clock frequency continues to change, now, however, increasing in value. Finally, after roughly 2 months of operation the clock appears to settle down to its quiescent, linear, frequency-aging rate. Note that the total change in lamp intensity during the warm-up period (days zero to one) is of the same magnitude as the total change in lamp intensity during both the equilibration (days one to ~30) and aging periods (days > 30).

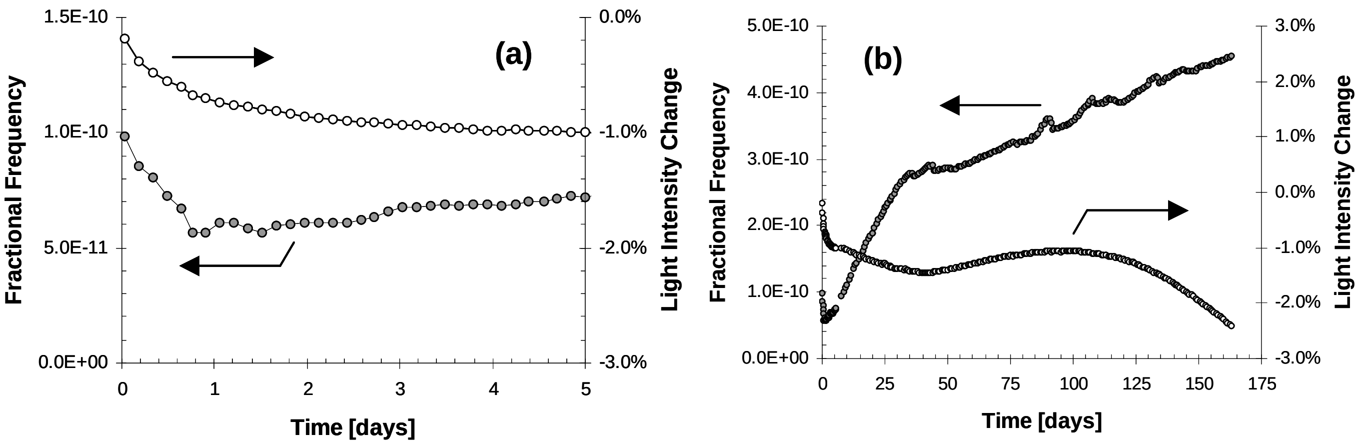

Figure 3. Rubidium clock frequency and lamp intensity versus time after initial activation for one of the FEI Rb clocks.

Figure 4 shows the correlation coefficients between clock frequency and lamp intensity for the three different periods of interest (i.e., warm-up, equilibration, and aging). Note that the correlation coefficient during the equilibration period is not only of a different magnitude from the light-shift coefficient, but also of a different sign. Consequently, for a causal relationship between clock frequency and lamp intensity during the equilibration period, we must posit a different light-shift mechanism during the equilibration period. For example, it could be that the warm-up causal mechanism is related to a "classic" light-shift effect (i.e., the lamp's spectral profile is a constant and only the light-intensity changes), while the equilibration mechanism is related to a more novel manifestation of the light-shift effect (e.g., the spectral profile of the lamp and its intensity are changing simultaneously). However, if this were true, we would then be left with the problem of explaining the aging period, where we get relatively significant changes in lamp intensity with little (linear) correlated change in clock frequency. Consequently, we seem forced to the conclusion that, during the equilibration and aging periods, the relationship between lamp intensity and clock frequency *is not* causal.[*] Nevertheless, the time scales of lamp intensity and clock frequency change are the same, and so it appears likely that the changes are driven by similar underlying mechanisms.

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see: B. Busca, M. Têtu, and J. Vanier, "Light shift and light broadening in the ^{87}Rb maser," **Canadian Journal of Physics, 51,** 1379-1387.

[*] Since the magnitude of the light intensity change is the same as what occurs during the warm-up period, it might seem that the clock frequency *must* change. However, as an example, in a Rb/Kr lamp the D_1 and D_2 lines of rubidium contribute roughly 50% of the total lamp light, with a good fraction of the rest of the lamp's light arising from the Kr buffer gas. Thus, the intensity of the alkali lines might remain relatively constant while the intensity of the buffer-gas light changes by a percent or two. For a discussion of the spectral components of Rb/Kr and Rb/Xe lamp lines see: J. Camparo, "Compendium of Milsat timekeeping: A collection of timekeeping documents from The Aerospace Corporation's Atomic Clocks Laboratory," Aerospace Report No. TOR-2002(1460)-1, 15 November 2001, Section II.A.

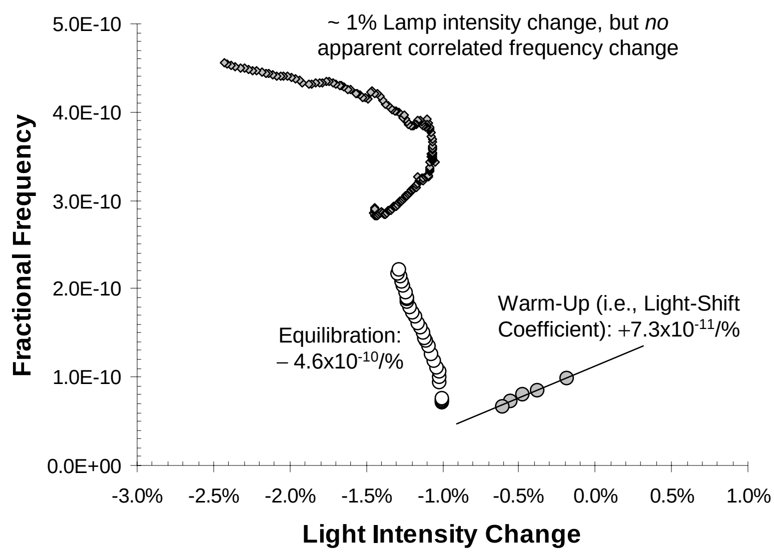

Figure 4. FEI Rb clock frequency vs. lamp-intensity change for the three different temporal periods of interest. Note that there is a very strong correlation between the clock's fractional frequency and the lamp's light intensity during both the warm-up and equilibration periods. However, defining the warm-up period's correlation coefficient as the light-shift coefficient, we see that the correlation coefficient during equilibration is of a different magnitude and sign. Consequently, we believe it unlikely that there is a causal relationship between clock frequency and the lamp's light intensity during the equilibration and aging periods.

Figure 5 shows the data from the PRS10 SRS rubidium clock. As in Figure 3, fractional frequency and percentage light-intensity change are plotted as a function of time since the clock's turn-on, and three periods are discernable: warm-up over day one, equilibration between day one and day 75-100, and aging beyond day 100. For this clock, we performed an additional test, turning the clock off at approximately day 100. It was then turned on briefly at day ~120 and then turned on for good at day 175. Note that the light intensity does not appear to age while the clock is off, though the fractional frequency does. Additionally, similar to the results from the FEI clock, the clock's light intensity and frequency change in a correlated fashion. Moreover, as with the FEI clocks and illustrated in Figure 6, while there is a strong correlation between clock frequency and lamp intensity after warm-up (but before the clock is turned off), the correlation coefficient does not equal the clock's light-shift coefficient. Additionally, after the clock is turned back on, though there is still a strong correlation between clock frequency and lamp intensity, the correlation coefficient has changed. Therefore, similar to the FEI clocks, evidence suggests that the relationship between clock frequency and lamp intensity is not causal after warm-up.

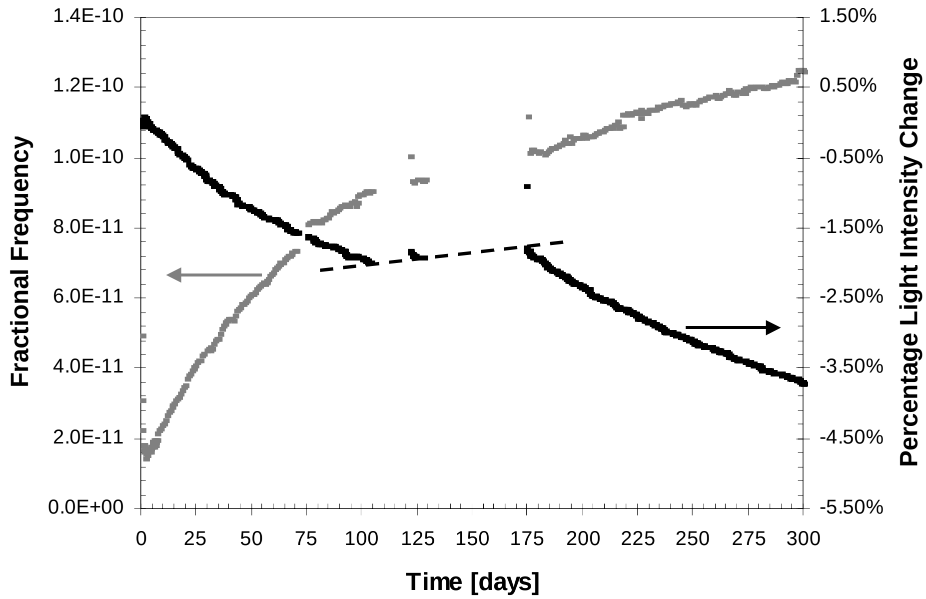

Figure 5. Clock frequency & lamp intensity vs. time after initial activation for the SRS Rb clock.

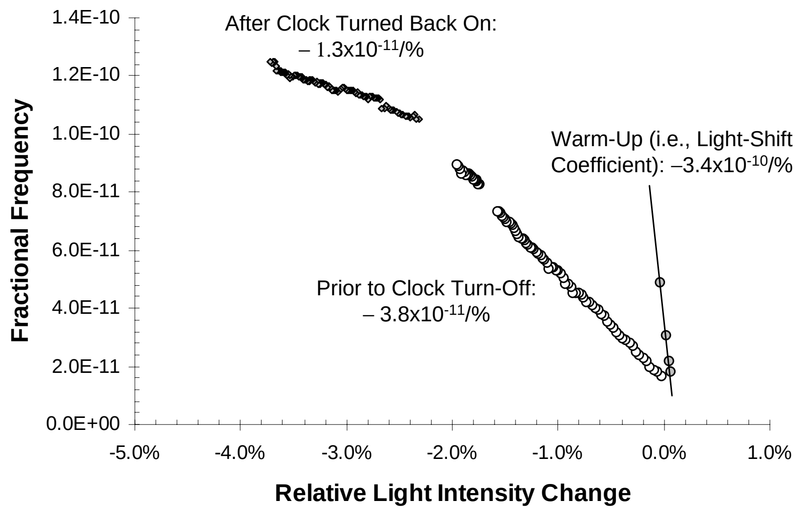

Figure 6. Similar to Figure 4, SRS Rb clock frequency vs. lamp-intensity change for the three different temporal periods of interest.

DISCUSSION

Though our study is still in progress, several results are emerging. First, Rb clocks appear to have three distinct (more or less) periods of operation: a warm-up period ($t \leq 1$ day), an equilibration period (1 day < $t \leq 10^2$ days), and an aging period ($t > 10^2$ days). Additionally, during the clock's warm-up and equilibration periods, the clock frequency and lamp intensity change in a correlated fashion, though with different correlation coefficients. These observations suggest that: 1) in addition to the classical light-

shift mechanism, the clock's frequency changes deterministically as a result of a second mechanism, 2) the time constant of this second mechanism is on the order of 10^2 days, and 3) this second mechanism likely plays a role in the equilibration and aging of the lamp's light intensity. For ease of discussion, we will refer to this second mechanism as the "X mechanism."

We can make our speculations a bit more concrete by writing the following expressions for the temporal change of the clock's fractional frequency, y, and total lamp intensity, I:

$$\frac{dy}{dt} = \left(\frac{\partial y}{\partial I_{Rb}}\right)\left(\frac{dI_{Rb}}{dt}\right) + \left(\frac{\partial y}{\partial X}\right)\left(\frac{dX}{dt}\right) \tag{1a}$$

$$\frac{dI}{dt} = \left[\left(\frac{\partial I_{Rb}}{\partial N_{Rb}}\right) + \left(\frac{\partial I_{BG}}{\partial N_{Rb}}\right)\right]\left(\frac{dN_{Rb}}{dt}\right) + \left[\left(\frac{\partial I_{Rb}}{\partial X}\right) + \left(\frac{\partial I_{BG}}{\partial X}\right)\right]\left(\frac{dX}{dt}\right) \tag{1b}$$

Here, I_{Rb} is the intensity of the optical rubidium resonance lines, I_{BG} is the intensity of the buffer-gas lines, and $\partial y/\partial I_{Rb}$ is the clock's light-shift coefficient. Thus, during warm-up X is assumed to change little, and the clock's frequency change and the lamp's intensity change are due primarily to a change in alkali density as the temperature of the lamp and filter cell approach steady-state conditions. Following warm-up, $dN_{Rb}/dt \cong 0$, and the clock's frequency and the lamp's intensity change as a result of the X mechanism. Since the X mechanism drives both the clock frequency and lamp intensity, they will change in a correlated fashion, though with a correlation coefficient that may differ significantly from $\partial y/\partial I_{Rb}$. Further, depending on the smallness of the light-shift coefficient, the X mechanism could affect the clock frequency directly (i.e., through the second term on the right-hand side of Eq. (1a)), or indirectly via the light-shift effect, i.e.,

$$\frac{dy}{dt} = \left(\frac{\partial y}{\partial I_{Rb}}\right)\left(\frac{dI_{Rb}}{dt}\right) = \left(\frac{\partial y}{\partial I_{Rb}}\right)\left(\frac{\partial I_{Rb}}{\partial X}\right)\left(\frac{dX}{dt}\right) . \tag{2}$$

One possible candidate for the X mechanism is helium permeation, since, as is well known, helium has a relatively high permeation rate through some glasses **[5]**. In order to explain the observations, we would assume that helium permeates through the resonance cell walls to shift the rubidium atoms' ground-state hyperfine splitting via the pressure-shift effect **[6]**, and additionally permeates through the lamp envelope to affect the lamp's output intensity **[7]**. Depending on the lamp and resonance cell glass types, the permeation rates could be correlated and could, therefore, give rise to a correlation between lamp intensity and clock frequency.

Another potential mechanism is a slow variation in resonant-circuit quality factors (i.e., Qs) as a result of alkali redistribution. Recent measurements in our laboratory have shown that the microwave cavity-Q of a gas-cell clock can change on a timescale of 10^2 days **[8]**, and as the cavity-Q changes, so too will the clock's frequency as a consequence of passive cavity pulling **[9]** and/or the position-shift effect **[2,10]**. Moreover, one should expect a similar alkali redistribution to occur in the lamp, and consequently a slow variation in the lamp resonant-circuit's quality factor. Thus, if resonant-circuit Q variations were the X-mechanism, changes in the microwave-cavity Q could directly affect the clock frequency, and changes in the lamp-circuit's Q could indirectly affect the clock frequency via the light-shift effect. Moreover, one would expect the rate of alkali surface diffusion in the lamp and resonance cell to have similar timescales, and to therefore appear to change in a correlated fashion. Obviously, further work is required both to

verify the characteristics of gas-cell clock equilibration and to gather further evidence on candidate X-mechanisms.

ACKNOWLEDGMENT

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QUESTIONS AND ANSWERS

ROBERT LUTWAK (Symmetricom): When you turned it off for two months and turned it back on again, it didn't re-equilibrate. Yet I imagine the clocks that you are testing were equilibrated back at the factory before you ever received them. So there is some difference between your turning them off and on and FEI turning it off and shipping it to you and you turning it on again.

JIM CAMPARO: That's right. And that is an uncontrolled parameter in our test. You know we have had this discussion. What we want to do when we order these clocks is to try and make sure that we get them with as little operation as possible before we put them under test. So, yes, you are absolutely right. That is an important parameter that we have got to consider as we keep this thing going and expand our database.